THE JOURNAL OF MICROWAVE POWER & ELECTROMAGNETIC ENERGY

A Publication of the International Microwave Power Institute

Subscriptions
Subscriptions are priced as follows: in the USA (third class mail); in Canada (first class mail); and elsewhere (air mail) $195 US funds drawn on a US bank. Subscriptions are available to individuals and organizations; back issue copies (1986-1997) are available, all earlier years are available on microfiche. **Purchase order, American Express, VISA or MASTERCARD** accepted. The Journal may also be obtained through leading subscription agencies at slightly higher rates.

Memberships
IMPI dues are $160 US for individuals and $1,500 US for corporations. For more information on Individual and Corporate memberships write to the IMPI office or e-mail *membership@impi.org*.

Manuscript submissions
The Journal welcomes the submission of articles on all non-communications aspects of electromagnetic energy. Authors article guidelines are provided on the inside back cover of this issue of the Journal. All manuscripts should be sent to Dr. Robert V. Decareau, Box 241, Amherst, NH 03031. News, Letters to the Editor, and commercial literature are also welcomed.

Copyright and reprint permission
Abstracting is permitted with credit to the source. Instructors may photocopy isolated articles for non-commercial classroom use without fee. For other copying, reprint, or republication permission, please contact the Executive Director.

The Journal of Microwave Power and Electromagnetic Energy is published and mailed quarterly by IMPI in Manassas, VA, USA.

For subscription, membership, microfiche, publication, and symposium information contact:

DEVELOPMENT OF PROCESS EQUIPMENT TO SEPARATE NONTHERMAL AND THERMAL EFFECTS OF RF ENERGY ON MICROORGANISMS

C. Brunkhorst, D. Ciotti, E. Fredd, J. R. Wilson,
D. J. Geveke, M. Kozempel

We developed a modified radio frequency (RF) dielectric heater, as a component of a continuous process, for isolating thermal and nonthermal effects of RF energy on microorganisms in liquid foods. The concept combines instantaneous input of RF energy to the food system with rapid removal of thermal energy. We used a double tube heat exchanger as an integral part of the RF heater. The outer tube was Teflon. The inner tube was stainless steel which was grounded in the RF circuit. Product flowed through the annular region between the two concentric tubes. Cooling water flowed through the grounded stainless steel tube. The RF energy was absorbed by the process fluid in the annular region. The cooling water flowing in the inner tube removed the thermal energy from the process fluid controlling the temperature.

ABOUT THE AUTHORS:
C. Brunkhorst, D. Ciotti, E. Fredd and J. R. Wilson are affiliated with Princeton Plasma Physics Laboratory, Princeton University, P.O. Box 451, Princeton, NJ. D. J. Geveke and M. Kozempel are affiliated with Eastern Regional Research Center, 600 East Mermaid Lane, Wyndmoor, PA.

Most liquid foods interact with high frequency electromagnetic fields, absorbing the energy and generating heat. The most common electromagnetic fields employed in the food industry are microwaves at 915 and 2450 MHz and radio frequency at a nominal 27 MHz. There has been an ongoing debate whether there are nonthermal effects associated with electromagnetic energy.

Just a few of the authors reporting results which appeared to indicate nonthermal effects are Culkin and Fung [1975], Webb and Dodds [1968], Webb and Booth [1969], and Olsen [1965]. Ramaswamy and Tajchakavit [1993] reported microwave energy was substantially more effective than conventional thermal energy for pectin methyl esterase inactivation indicating the possibility of some complementary nonthermal effects. Reznik and Knipper [1994] reported liquid egg pasteurized with a combination plate and frame heat exchanger followed by an RF electric heater exhibits several distinct advantages over conventionally pasteurized liquid egg. There is a higher degree of microbial kill. There is less regrowth of bacteria even when the egg is maintained at room temperature. In the refrigerated liquid egg, bacteria counts actually decreased for a few days after processing.

However, for every author reporting an apparent nonthermal effect there is another author reporting no such thing, such as Carroll and Lopez [1969] and Goldblith and Wang [1967]. Mertens and Knorr [1992] published an excellent review of nonthermal processes for food preservation. After presenting both sides of the debate, they concluded "whether or not these phenomena are real and can be applied in the food industry remains questionable and still needs to be demonstrated".

Several theories have been advanced to explain how electromagnetic energy kills microorganisms. These theories are summarized in a review by Knorr et al. [1994]. There is the "dielectric rupture theory" of Zimmermann et al. [1974] in which an external electric field induces an additional transmembrane electric potential which is larger then the normal potential of the cell. At sufficient potential the cell membrane ruptures, resulting in pore formation, increased permeability, and
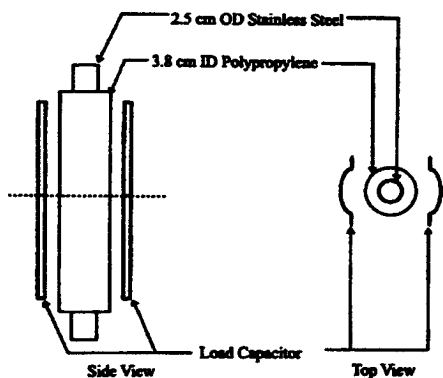
FIGURE 1: Initial Load Configuration. Capacitor is 76.2 cm long and 7.0 cm wide.

lost cell integrity. The required electric field for electroporation is on the order of 20 kV/cm. However, this is much greater than that used in the food industry and by the authors cited above.

Kinosita and Tsong [1977] presented a mechanism for pore development caused by pulsating electric fields. They presented evidence of migration of species across the cell membrane and resultant destruction of the cell.

Mertens and Knorr [1992] discuss the use of oscillating magnetic fields disclosed in a world patent [Anon, 1985]. "The patent suggests that the oscillating magnetic field couples energy into the megneto-active parts of large biological molecules with several oscillations. When a large number of magnetic dipoles are present in one molecule, enough energy can be transferred to the molecule to break a covalent bond. It is assumed that certain critical molecules in a microorganism, like DNA, or proteins, could be broken by the treatment, hence destroying the microorganisms or at least rendering it reproductively inactive."

The objective of this study was to develop a modified RF heater, as a component of a continuous food process, capable of separating thermal and nonthermal effects of RF energy on microorganisms in liquid foods.

Materials and Methods

The RF equipment is a Model FH-10, 15kW Radio Frequency Heater (PSC, Inc., Cleveland, OH). The oven consists of a power oscillator, including an EIMAC 3CX10000H3 triode. The plate supply is an unfiltered three phase transformer-rectifier, with 480 VAC input. The absence of a filter capacitor minimizes stored en-

ergy and thus the hazards to the tube and personnel. The plate voltage is set by an SCR controller, and is variable from 2 to 12 kV. The plate voltage controls the level of the RF power.

We measured exposure levels with a Narda meter, model 8616, and probe, model 8682 (Loral Microwave NARDA, Hauppauge NY), which reads directly in percent of the ANSI standard. The ANSI standard has been incorporated into the IEEE C95.1-1999 standard. The ANSI standard for safety levels with respect to human exposure to electromagnetic fields establishes a maximal permissible limit for E field strength of 4000 V^2/m^2 at our frequency of operation. The ANSI standard is actually an E field limit, but it is based on the ability of RF to heat human tissue, so it is commonly expressed as an equivalent power density. This is the power density that would result from a plane wave of the stated E field strength. The limit we used was for 30-300 MHz, and we were actually at 18 MHz with water as the test fluid. Below 30 MHz the limit is $900/f^2$ (f in MHz), and would be 2.8 mW/cm^2 at 18 MHz. However, since the frequency is dependent on the different test fluids, we chose the more conservative limit.

Princeton Plasma Physics Laboratory

The initial load consisted of two concentric pipes, as shown in Figure 1. The inner pipe was 2.5 cm OD stainless steel, and carried cooling water. This pipe was grounded. The outer pipe was 3.8 cm ID polypropylene, and the liquid food test fluid flowed in the annular region between the two pipes. This assembly was flanked on either side by concave aluminum capacitor plates, which coupled RF energy to the test fluid through the polypropylene pipe wall. The plates were 7.0 cm wide and 76.2 cm long. The spacing from the plates to the pipe was variable. In the oven's original configuration, one plate was grounded, and the other was driven, as shown in Figure 2. When operated in this configuration, coupling of significant power to the test fluid was hampered by arcing at the load capacitor. For our tests, water was circulated through both pipes. The water was supplied by a 208 L storage tank and a small pump via PVC piping. The flow was divided, one part directed through the 2.5 cm pipe, and the other through the annular space between the pipes. Both flows were recombined after their passage through the pipes.
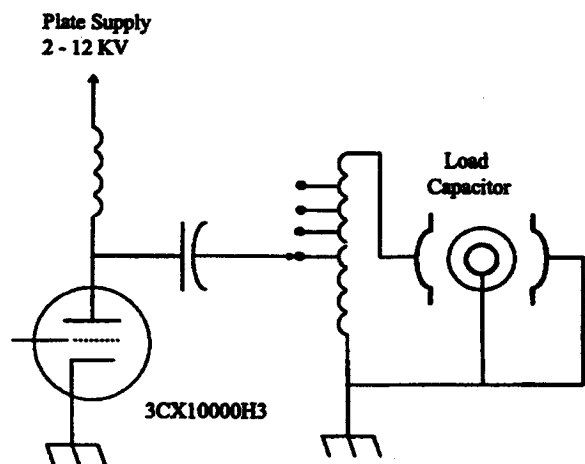
FIGURE 2: Initial Circuit Configuration.

Temperature measurements were made of both the combined flow, and the flow in the annular region with Type K thermocouple probes. The temperatures were displayed on two Fluke model 52 dual input thermometers, as either the individual readings or as a temperature difference, ΔT. Power into the load is calculated by $P = 69.7*\Delta T*Qw$, where P is in Watts, Qw is water flow in kg/min and ΔT is in °C. The conductivity of the water/sodium carbonate solution was measured with a Fischer Scientific model 09-326-2 conductivity meter.

Eastern Regional Research Center

The RF heater, modified at the Princeton Plasma Physics Laboratory, was installed at the Eastern Regional Research Center. Experiments were performed in which liquids were supplied with RF energy while simultaneously being cooled. The equipment consisted of a double pipe heat exchanger inside a RF chamber. The outer pipe was Teflon™ that is transparent to RF, whereas the inner pipe was stainless steel through which water flowed to regulate the temperature. Process fluid flowed in the annulus and absorbed the RF energy. Water flowed co-current to the process fluid and removed thermal energy from the process fluid.

The experimental system is shown in Figure 3. It includes an 190 l stainless steel feed tank. A sanitary positive displacement pump, Tri-Clover, Kenosha, WI, model PR3-1M-YH6-ST-S, supplied the feed to the RF heater at a flow rate of 3 kg/min. The outer pipe of the double pipe heat exchanger had an inner diameter of 3.8 cm. The inner tube had an outer diameter of 2.5 cm. To achieve turbulent flow while maintaining a reasonable treatment time in the RF heater, a second sanitary positive displacement pump, Tri-Clover rotary pump, model PR25-1-1/2M-UH4-ST-S, recycled the process fluid. The recycle pump circulated the fluid at 9 kg/min, sufficient to achieve turbulent flow. Based on the feed and recycle rates, the process fluid, on average, passed through the RF heater four times. The cumulative treatment time in the RF heater was 8.4 s. By adjusting the feed and recycle rates, residence times ranging from 7.3 s to 16.8 min can be obtained. Process fluid exited the recycle loop in direct proportion to the feed rate established by the feed pump. The system can be visualized as a continuous stirred tank that receives RF energy.

FIGURE 3: Process Flow Sheet of the RF heater at ERRC.
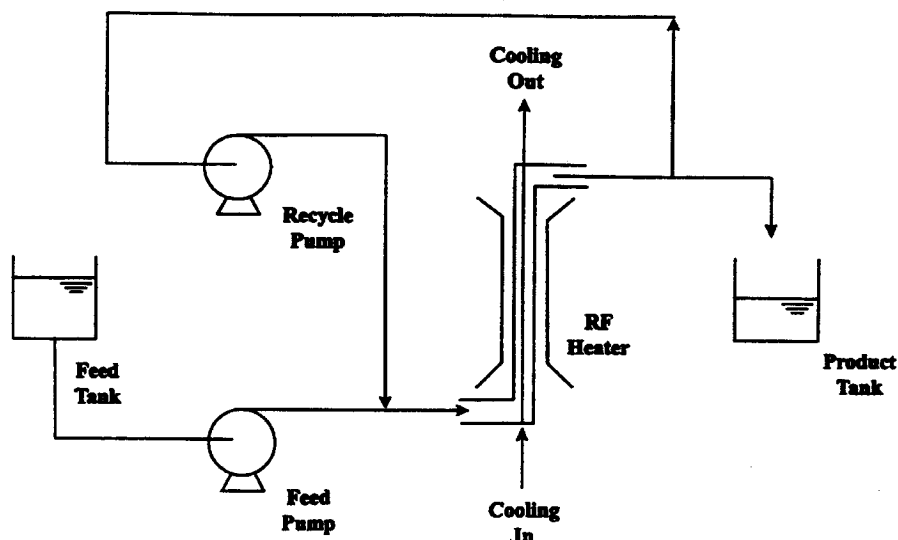
The geometric arrangement of the capacitor plates and inner tube resulted in the application of a nonuniform RF field to the process fluid; the electric field strength of the fluid nearest the plates was approximately three times that of the fluid farthest from the plates. However, in addition to providing turbulent flow, the recycle minimized the nonuniformity by averaging out the differences.

RF power was applied at 19 kW. A fiberoptic thermometer, Luxtron, Santa Clara, CA, model 950, provided the temperatures of the feed tank, water, and process fluid. The temperatures were continuously logged to a data acquisition system.

Results and Discussion

Princeton Plasma Physics Laboratory

The holes in the oven where the pipes exit were stuffed with a copper mesh material for RF shielding. Ferrite common mode suppressors were placed on the thermocouple leads. A Narda RF leakage detector meter indicated only 5 % of the ANSI standard. Locating the tank about 3 m away and the thermocouple probes and meter used to measure the ΔT of the combined flow near the tank, provided reliable readings for the combined flow.

The combined flow was set to 15.2 kg/min, and the annular flow to 7.6 kg/min. The load capacitor plate spacing was initially set to 10.2 cm from the polypropylene pipe to the active plate, and 6.4 cm from the pipe to the grounded plate. At the full plate voltage of 12 kV, the ΔT for the combined flow was less than 1°C, and the frequency was 24 MHz. Sodium carbonate was added to the water to increase its conductivity, and the spacing from the capacitor plates to the pipe was reduced to 2.5 cm to the active plate and 1.3 cm to the grounded plate. The ΔT was 1°C at 10 kV, with 0.3 A of plate current. The polypropylene pipe deformed due to localized heating. It was replaced with Teflon, and the load capacitor circuit configuration was changed so that both plates were connected together (driven in-phase).

The plate that was formerly grounded was supported on ceramic insulators. The ground connection to the stainless steel pipe was improved by adding more grounding straps. With both capacitor plates at 1.3 cm from the Teflon pipe, a 1.5°C ΔT was obtained at 12 kV and 1.4 A. This represents 1.5 kW delivered to the load. The capacitor plate spacing was then reduced to 0.6 cm. At

10 kV and 0.6 A of plate current, the ΔT was 2.4°C, at which point arcing occurred at the top of the capacitor plate. This demonstrated both the benefit of increased coupling, and the hazard of higher voltage stress at close plate spacing. The Ceramic insulators heated up, so they were replaced with Rexolite, a plastic material. The insulators on the other capacitor plate are made of steatite, and remained cool. The edges of the capacitor plate were rounded with a file to reduce the tendency for arcing.

Operation was attempted with the capacitor plates in contact with the Teflon pipe; but the best result was only a 0.6°C ΔT. The plates were returned to 1.3 cm spacing. Arcing was observed at the load at a plate voltage of 7 kV and a ΔT of 1°C.

To improve arc suppression and allow better coupling, sheets of dielectric material were placed between the capacitor plates and the pipe, in contact with both surfaces. The material was 1.3 cm polyethylene, and extended 7.6 cm beyond the edges of the capacitor plates. This material has a dielectric constant of about 2 which increased the capacitance, and thus the coupling of the load capacitor over that of an equal spacing in air. At 7 kV plate voltage and 0.6A plate current, a ΔT of 1.6°C was obtained. At 7.4 kV, arcing occurred at the top of the capacitor plate.

New capacitor plates were manufactured of 1.0 cm thick aluminum, 7.6 cm wide by 91.4 cm long. The edges were milled with a 1.0 cm radius, and were bent 60° for 7.6 cm at the ends. Larger (109.2 cm by 15.2 cm) dielectric plates were also built. The new capacitor plates are of flat cross section along their short dimension, rather than concave. At 8 kV and 0.9 A, the ΔT was 3.1°C. At 8.8 kV, arcing was noticed. It was coming from the copper mesh material used to provide a RF shield at the pipe exit holes. Large ground currents were forced to flow through this material, which was making loose contact. Better RF shielding and grounding was required. The holes were reduced from 12.1 cm to 5.1 cm diameter with copper plates, and the gap to the stainless steel pipe was completely enclosed with sections of 2.5 cm wide copper braid. One end of the copper braid was soldered to the copper plate, and the other clamped to the stainless steel pipe.

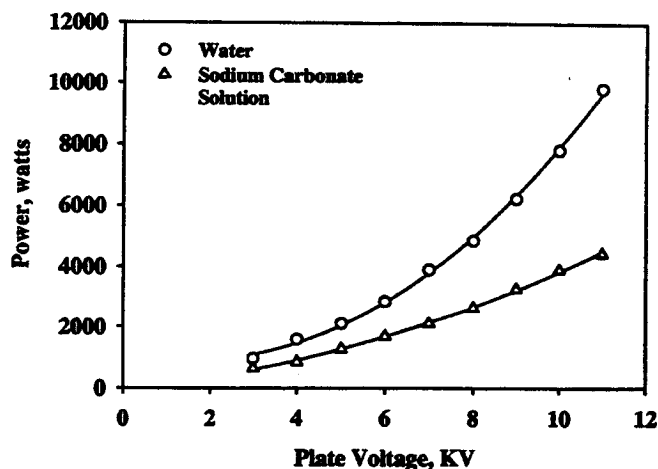Testing of the new configuration produced a 4.5°C ΔT at 11 kV and 1.0 A. The frequency had dropped to 18

FIGURE 4: *Power Delivered to the Load vs. Plate Voltage.*

of 7.84 kW, a plate input power of 15 kW and an efficiency of 52%. Figure 4 is a graph of power delivered to the load vs. plate voltage. Curves are shown for both water and sodium carbonate solution as the test fluid.

Some final modifications were made to improve the mechanical stability of the dielectric plates. Teflon studs were installed to keep the dielectric plates centered in the capacitor plates. Satisfactory operation was demonstrated at sustained full power. The final mechanical and electrical configuration of the load is shown in Figure 5 and 6.
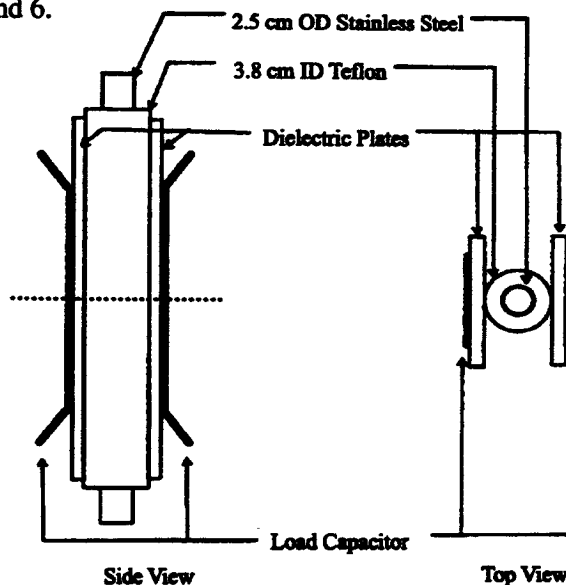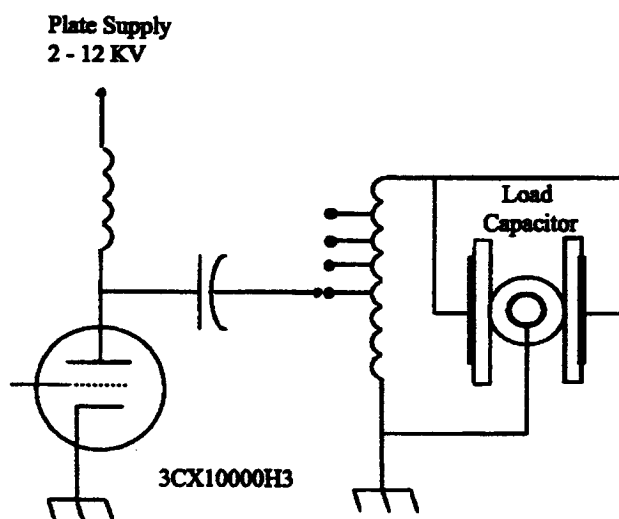

FIGURE 5: *Final Load Configuration.*

MHz due to the increased capacitance of the load. The RF leakage was greatly reduced. The increased coupling of the new capacitor is due to its flat surface, which brings its entire area into contact with the dielectric plate, resulting in an increase in capacitance. The original capacitor plates were concave, and only contacted the dielectric plates at their edges.

The Rexolite insulators for one capacitor plate partially melted, and were replaced with Teflon insulators. The edges of the opening, where the aluminum tank circuit connection passes from the oscillator compartment to the load compartment, were covered with split rubber hose to form a corona shield.

The next attempt produced a 4.8°C ΔT at 11.4 kV and 1.0 A. This was the maximum voltage available under load. After 10 minutes of full power operation, there was an arc at the top of the capacitor plate. Corona shields were made and installed to eliminate the sharp edge on the radius at the plate ends. The next run produced a 4.7°C ΔT at 11.8 kV and 0.95 A. This represents an efficiency of 44%. No arcs were observed at the load. The conductivity of the water/sodium carbonate solution was 3.58 mS/cm at 24°C. As a comparison, tap water was measured at 0.29 mS/cm, and apple juice was 2.08 mS/cm.

For the final test, the sodium carbonate solution was drained and the tank was refilled with water, the conductivity of which was 0.362 mS/cm at 21°C. The ΔT was 7.4°C at 10 kV and 1.5 A. This represents a load power
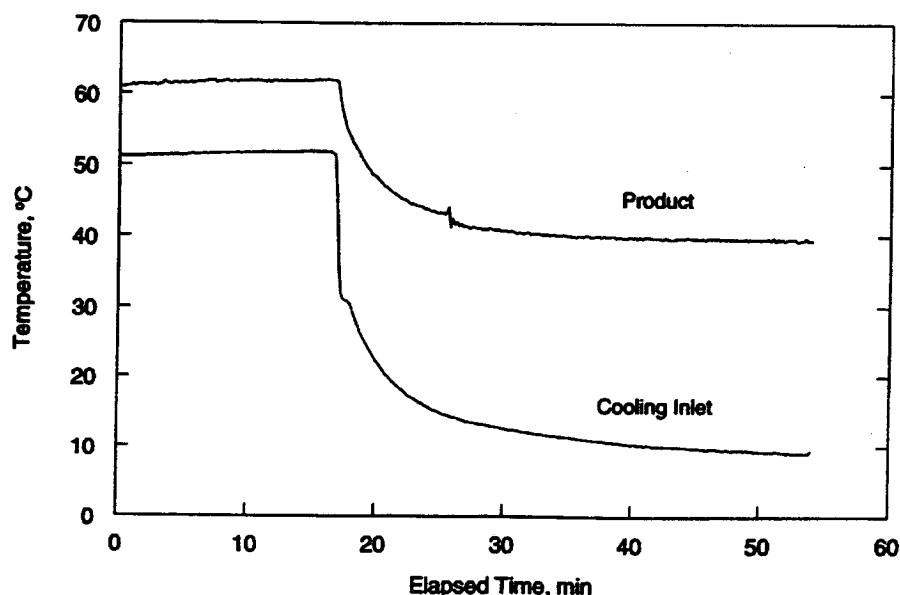

FIGURE 6: *Final Circuit Configuration.*

FIGURE 7: Thermal vs. Nonthermal Test. Process temperature controlled by only varying the cooling water inlet temperature. All other parameters kept constant: RF power supplied, 19 kW; feed rate, 3 kg/min; feed temperature, 11°C; recycle pump rate, 9 kg/min. Each line consists of 324 data points.

Eastern Regional Research Center

The experimental procedure to isolate nonthermal from thermal effects is to run the process at normal pasteurization temperature, usually at 60-65°C, and, without changing anything such as power input or product flow rate, to drop the temperature to 40°C using only cooling water in the inner tube. Any microbiological reduction of the product at 40°C would be due to nonthermal effects.

To test solely the performance of the unit, tap water with no added microorganisms was processed at normal pasteurization temperature. As shown in Figure 7, cooling water in the ground pipe quickly reduced the product temperature to 40°C. Several other liquids, such as apple cider, beer, and deionized water, have been tested with similar results.

Conclusions

The RF heater was successfully modified. It is capable of isolating thermal and nonthermal effects due to RF. As such, we will begin testing for nonthermal effects on microorganisms in liquid foods.

Note: Mention of brand or firm name does not constitute an endorsement by the U.S. Department of Agriculture above others of a similar nature not mentioned.

References

Anon. 1985. Deactivation of microorganisms by an oscillating magnetic field. World patent 85/02094. Assigned to Maxwell Laboratories, Inc., San Diego, California.

Carroll, D.E. and Lopez, A. 1969. Lethality of radio frequency energy upon microorganisms in liquid, buffered, and alcoholic food systems. J. Food Science 34(4): 320-324.

Culkin, K.A. and Fung, D.Y.C. 1975. Destruction of Escherichia coli, and Salmonella typhimurium in microwave-cooked soups. J. Milk Food Technol. 38(1): 8-15.

Goldblith, S.A. and Wang, D.I.C. 1967. Effect of microwaves on Escherichia coli and Bacillus subtilis. Applied Microbiology 15(6): 1371-1375.

Kinosita, K., Jr. and Tsong, T.Y. 1977. Formation and resealing of pores of controlled sizes in human erythrocyte membrane. Nature 268(5619): 438-441.

Knorr, D., Geulen, M., Grahl, T., and Sitzmann, W. 1994. Food application of high electric field pulses. Trends in Food Science & Technology 5(3): 71-75.

Mertens, B. and Knorr, D. 1992. Developments of nonthermal processes for food preservation. Food Technology 46(5): 124-133.

Olsen, C.M. 1965. Microwaves inhibit bread mold. Food Engineering 37(7): 51-53.

Ramaswamy, H.S. and Tajchakavit, S. 1993. Continuous-flow microwave heating of orange juice. Paper No. 933588 at the ASAE Meeting.

Reznik, D. and Knipper, A. Method of electroheating liquid egg and product thereof. U.S. patent 5,290,583. May 1, 1994.

Webb, S.J. and Dodds, D.D. 1968. Inhibition of bacterial cell growth by 136 gc microwaves. Nature 218(5139): 374-375.

Webb, S.J. and Booth, A.D. 1969. Absorption of microwaves by microorganisms. Nature 222(5199): 1199-1200.

Zimmermann, U., Pilwat, G., and Riemann, F. 1974. Dielectric breakdown of cell membranes. Biophys. J. 14(11): 881-899.

JOURNAL OF MICROWAVE POWER
AUTHORS' INSTRUCTIONS

1. **MANUSCRIPTS**: must be in English including **one original and three duplicates**. All copies must be typewritten, double-spaced, on one side of the paper and have a one-inch (2.5 cm) margin on all sides.

    Manuscripts and correspondence should be sent by first-class mail, or airmail, to the **Editor in Chief, Journal of Microwave Power and Electromagnetic Energy, Box 241, Amherst, NH 03031.**

2. **TITLE PAGE**: must contain:
    * a brief, informative title
    * the name(s) and institutional affiliation(s) of the author(s), and
    * the address, telephone number, fax number and e-mail address to be used for correspondence.

3. **ABSTRACTS**: must be a factual condensation of the article, including a clear description of the major findings, presented in **100 words or less**.

4. **TEXT**: full-length articles should be organized into sections with clear headings, e.g., Introduction, Materials and Methods, Results, Discussion, Conclusions, and References, all not to exceed 20 double-spaced pages, exclusive of figures and tables.

All text *MUST* :
* **be generated with a carbon ribbon**
* **have good quality type with no broken, run-together or blurred characters, and _NOT_ be right justified.**

Laser printer copy may also be submitted, and a copy of the final manuscript (with text in Times 10 point font) on computer disk is requested and preferred. Macintosh disks are preferred. Preferred format for IBM disks is Microsoft Word. Preference is given to those authors who provide a disk.

---

5. **EQUATIONS & FORMULAS**: must be shown on a separate line of the text and numbered (in parentheses) at the right margin. Text citations must indicate the number of the equation.

6. **REFERENCES**: in the text must be cited by author and year of publication. All reference citations must be pre-

sented at the end of the article, listed in alphabetical order. Text citations will use brackets; e.g. [Johns and Cole, 1982]; [Cole, et.al., 1985]; "Cole et. al. [1985] reported...". The following examples for the preferred reference citations are given:

Cole, E., Smith, G.H., and Goldfarb, R. 1985. Dielectric properties of barley. J. Microwave Power 9: 5-10.

Johns, A. and Cole, E. 1982. Microwave economics for the eighties. Gebbie 1: 9-12.

7. **TABLES**: should be typed, double-spaced, in the same typeface as the article text and on separate sheets. Each table must have a self-explanatory title, be numbered with Arabic numerals in the order of appearance and be keyed to the text.

8. **FIGURES**: must be consecutively numbered with Arabic numerals, each on a separate sheet, in the order of their appearance and must be keyed to the text. Line drawings must be of high quality in pen and ink and must include submission of an original or a high-contrast, glossy print. Photomicrographs and other half-tone photographs should be high-contrast, black and white, glossy prints. All figures must be presented in **black and white only with no background screens** and be properly labeled with the author's name, figure number and orientation.

9. **LEGENDS**: must accompany each figure to enable readers to identify and understand the figure apart from the text. All abbreviations and values must be defined in the legend.

10. **GENERAL COMMENTS**: All submissions to the *Journal of Microwave Power and Electromagnetic Energy* must indicate whether the paper is being submitted solely to the *Journal*. Any article submission that has been submitted to (or printed by) any other publication (in part or in whole) must identify all other such publications and their submission or publication date. The author's institution will be asked to volunteer a page charge of $50 (U.S.) per page which entitles the institution to 100 free reprints. Additional reprints may be purchased from the publisher.
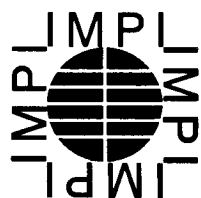
INTERNATIONAL MICROWAVE POWER INSTITUTE
10210 Leatherleaf Court, Manassas, VA 20111 USA
Telephone: (703) 257-1415 • FAX: (703) 257-0213
E-Mail: info@impi.org • Web URL: www.impi.org

In This Issue:

NON PROFIT ORG
U.S. Postage
PAID
Centreville, VA 20120
PERMIT #50